‘1’111{ ADVANCED l’ll(Y1’OVO13’AIC SOLAR ARRAY PROGRAM UPDATE

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ABSTRACT

The paper continues the status reporting of the development of an ultralightweight flexible blanket, flatpack, foldout solar array testbed wing that was presented al the First and Second European Space Power Conferences (Ref. 1 and 2). To date a testbed wing has been built and subjected 10 a variety of critical functional tests before and after exposure 10 simulated launch environments. This paper reviews the latest design details, fabrication activities,]Jallcl-level tests dealing with reverse bias characterization of thin silicon solar cells, and wing level environmentaltests.The t,c~,illlirl~-c,f-life. (BOL) specific power estimates for a nominal](I kW (BOL) array remains above 135 W/kg, with corresponding clld-of-life (EOL) performance above 90 W/kg for a 1 () year geosynchronous (GEO) mission.*

Key Words: photovoltaic solar arrays, flexible blanket, thin solar cells, reverse bias protection, testbed hardware development.

1. INTRODUCTION

The Advanced Photovoltaic Solar Array (APSA) program, begun in 1985, Successfully completed its primary objectives in 1991 with the design, development and testing of a prototype testbed wing. The approximately 6 kW (1101,) wing design was shown to be capable of providing over 130 W/kg (BOL) specific power as an intermediate milestone towards NASA’s far term goal of 300 W/kg at 20 kW. The design represents a three-fold improvement on the performance of current rigid-panel arrays and a factor of two improvement on the performance of an advanced flexible-blanket wing developed earlier by NASA office of Advanced Concepts and Technology (OACT) (Ref. 3) and in Europe for the Olympus Satellite (Ref. 4). As will be discussed later, the APSA system already has been employed as a testbed to evaluate future advanced photovoltaic cic.vices and structural elements 10 enhance performance levels. In addition, a modified version of the APSA design using gallium arsenide (GaAs/Ge) solar cells with a more rigid blanket construction has been selected by General Electric (now Martin Marietta) for NASA’s Earth Observing System (EOS-AM) solar array

The last stage of the APSA program has been in progress about one year with a number of analyses and panel-level tests to better define a variety of design options, to support flight hardware experiments on host spacecraft, and to enhance the overall operational reliability of flexible-blanket array designs under conditions where the solar cell circuits are shadowed Or contain cracked solar cells. Although [hc final rc.suits are not yet available. on all the on-going activities, the nature of the effort in progress is summarized anti results of some of the flight test hardware. are presented.

2. DESIGN DESCRIPTION

2.1 Generic Configuration

The basic design configuration is shown in Fig. 1. The deployed and stowed size for the baseline 5.8 kW (BOL) wing are shown in Figs. 2. and 3. Two wings of this configuration can provide a spacecraft with 11.6 kW (BOL) and 7.8 kW (EOL) powr after 10 years in GEO orbit. The wing consists of a flatfold, multiple panel, flexible blanket cm which solar cell modules are installed and connected to printed circuit electrical harnesses that run along the outside longitudinal edges of the blanket assembly. For launch, the accordion-folded blanket is stowed in a graphite/epoxy blanket housing assembly with a polyimide foam layer on the inner surfaces to cushion the folded blanket during launch. There is no interleaving cushioning material between the folded panels. Solar cells from adjacent panels arc in direct contact when the blanket is folded and stowed in the blanket housing assembly under a preload pressure of 3500 to 7000 Pa (0.5 to 1 psi). The blanket is deployed (unfolded) by extending a motor-actuated, fiberglass, continuous longeron lattice mast that uncoils from an aluminum cylindrical canister structure. The blanket is supported by two tensioned guidewire systems attached to the rear foldlines of the blanket 10 prevent any large out-of-plane excursions during deployment. When fully deployed, the blanket is tensioned in the longitudinal direction by a series of cmls[all[-force springs at the inboard end of the blanket.

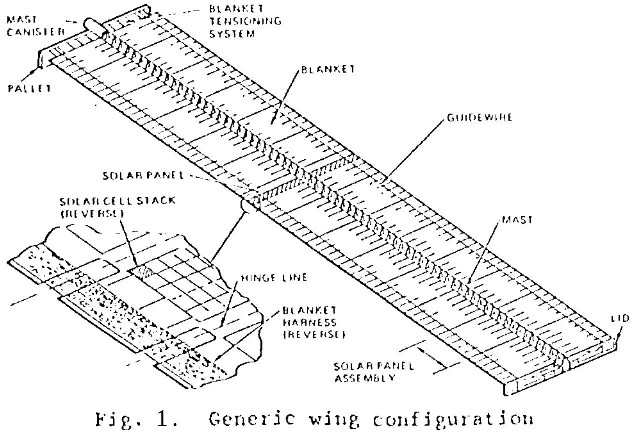

Fig. 1. Generic wing configuration

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* The research described in this paper presents the results of one phase of research carried out by TRW Space and Electronics Group and the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

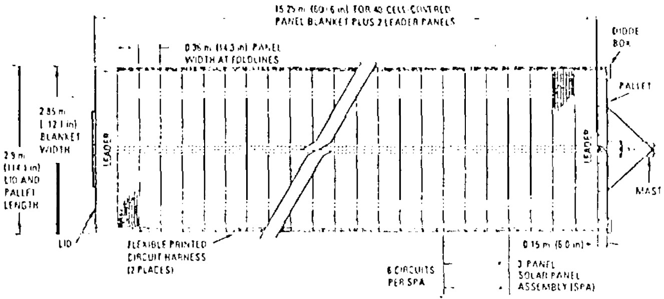

Fig. 2. 5.8 kW (BOL) GEO deployed wing.

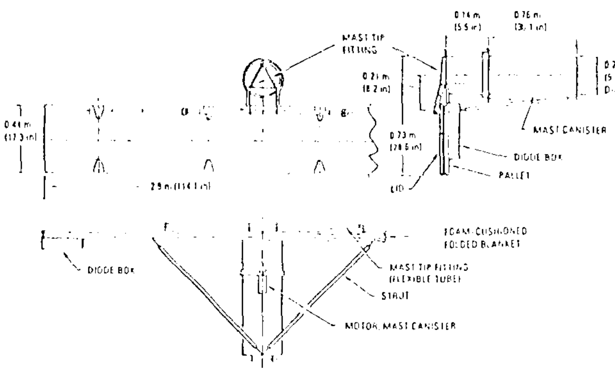

Fig. 3. 5 . 8 kW (BOL) GEO stowed wing.

Over the last year the baseline design has seen only minor changes rrs the result of ongoing analyses or component/system level tests:

1) For ultralightweight applications, the carbon-loaded Kapton blanket substrate material was replaced by germanium-coated regular Kapton. The germanium coating has the same surface resistivity as the carbon-loaded material to permit grounding of the blanket substrate to prevent electrostatic charge buildup from orbital plasma environments. 11 is also very resistant 10 atomic oxygen degradation thus providing long term protection for low earth orbit (1 .EO) missions. It also has favorable thermophysical properties ($\alpha/\varepsilon \approx 0.5/0.8$) thereby reducing the heat loading and operating temperature of the solar cell circuits by up to 15°C from the 1 .EO earth's heating.

2) Bypass diodes are integrated into the solar cell circuit design 10 ensure reliable power performance of the array when subjected to shadowing or as the result of cracked cel ls. The preliminary requirement reported in 1991 to have. a thin wafer diode bypass every eight cells is currently under review based on a series of cell-and circuit-level tests and analysis. Final guidelines won't be available. for several months. However, it is clear that the use of thin silicon cells will require the protection of shunt diode.s. Analysis and tests not funded under the APSA program also show this to be true for GaAs/Ge cells on a thin blanket substrate.

3) Under TRW discretionary funding a heavier, alternate blanket construction was clc.vc.loped that replaces the single Kapton layer with a germanium-coated Kapton/graphite composite laminate. While 4 times heavier, the substrate eliminates the need for shunt diodes when using GaAs/Ge cells and may reduce the number of shunt diode.s required for silicon solar cell circuits. A full size 3-panel solar panel assembly was constructed with thin large. area GaAs/Ge cells and incorporated into the APSA wing. Stowed wing vibration tests successfully demonstrated the. viability of the design concept. This substrate design with GaAs/Gecells has been incorporated into the flight hardware design for the EOS-AM solar array.

2.2 Blanket Assembly

The baseline blanket substrate material is 50-µm (2 roil) thick gcrrlla!litlrl~-coated Kapton polyimide film. The 42-panel 5.8 kW (BOL) wing blanket assembly consists of 14 three-panel solar panel assemblies (SPAs). Forty of the 42 panels arc. covered with solar cells. Twelve of the 14 SPAS are fully covered with solar cells. For the other two SPĀs, Iwo of the three panels in each SPA arc, covered with solar cells and the remaining panel is left blank to act as a leader panel. The inter-SPA hinge lines are unreinforced Ilcat-set crease folds in the Kapton material. Each SPA is linked to the next SPA through a piano hinge constructed along each outer lateral edge of the SPA. The hinge pin is a 1.3-mm (50-mil) diameter pultruded graphite/epoxy rod.

Currently each cell-covered panel has six rows of 2.0 x 5.7-cm cells, with each row containing 120 cells. There are 28,800 cells per blanket assembly. The solar cell stack consists of: (a) 50-µm (2-mil) thick ceria-doped cover glass coated on the front surface with a UV/AR filter; (b) 55µm (2.2-mil) thick 10 Ω-cm boron-doped, back surface field, aluminum back surface reflector, polished silicon solar cell (η_0 = 13.8 percent at 28°C AhI()); (c) two inplane stress relief loop silver-plated Invar interconnectors soldered [o the solar cell in a front/back fashion; and (d) DC 93500 silicon adhesive bondlines. Panel-level packing factor for cell installation is 0.86 (-760 cells per m^2) exclusive of the electrical harness regions, and 0.79 including the harness regions. Cell rows arc arranged in a serpentine manner so string-turnaround occurs at the center of each panel and the. string returns to the outer edge of the. panel. An electrical circuit string consists of 360 cells in series (6 rows by 60 cells pcr row) to obtain an EOL peak power voltage of 142 V. There arc two-Ujlirror-imaged circuits per Market panel. A thin, 0.4 x 2.8 cm, flat wafer bypass diode is planned for every 8 silicon cells (subject to later rc.view when all panel-level tests and analyses arc c4mlplc.led).

All positive and negative terminations for each circuit (and grounding of each pane.]) occur along the outside edge of the SPA adjacent to a printed circuit harness that is bonded to the basic blanket substrate. The harness runs from the. outboard leader panel to a diode box on the under side of the pallet structure. There arc. 80 copper traces per each 1 2-cm (4.6-in) wide. harness run. The trace.s arc. 2 oz copper 0.79-mm (31-roil) wide. by 68-µm (2.7-mil) thick with 0.5-mm (20-mil) spacing. The traces were sized to carry at least 0.4A (positive traces) and 0.8 A at 142. V (negative traces) with a net harness/diode. drop of about 2 percent (~3.2 v).

2.3 Blanket Housing Assembly

The blanket housing lid and pallet structures arc essentially identical in size and construction. The 0.44-m wide 2.0-m long

(1 '7.3 by 114.1-in) lid and pallet panels are constructed from 250-μm (10-mil) thick high-modulus 1'100 graphite/epoxy farx-sheets bonded to an aluminum honeycomb core 1 3-mm (0.5-in) thick with local facesheets and core reinforcements in high stress regions. Attached to the inside, surface of the lid and pallet panels is a polyimide foam cushion layer.

Figure. 4 illustrates Lhc motor-actuated mechanism used 10 simultaneously rc.lease the latches that secure the lid to the pallet structure before deployment of the blanket. The lid is clamped to [hc pallet structure with braided steel cables al four locations along the length of the housing structure. The hook latches are locked in place by small graphite/epoxy pushrod struts that are connected to an over-center crank on a central graphite/epoxy torque tube.

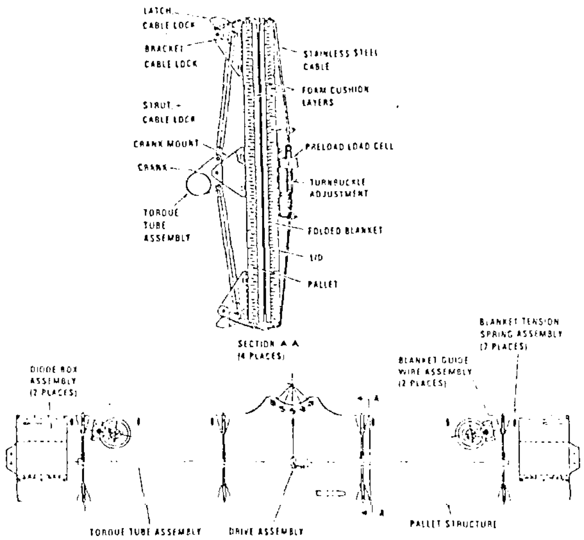

Fig. 4. Stowed blanket preload/release mechanism

The guidewire systems attached to the rear foldlines of the blanket assembly are each tensioned to 5 N (1lb). To ensure acceptable deployed wing dynamic characteristics and prevent the blanket from "slapping" the mast structure when subjected to 0.01-g inertial loads, the. deployed blanket is tensioned to 45 N (10 lb) via seven collslallt-force springs distributed along the inboard edge of the blanket.

2.4 Blanket Deployment System

Figure 5 illustrates the mast system. It is a carlistc.r-deployed, continuous longeron lattice mast similar in configuration to that used on the SAFE and Olympus solar an ay wings. A major accomplishment under the APSA program was to weight-optimize the design of the mast system, especially the canister structure anti deployment mechanism. The mast system was sized to meet 0.10 Hz and 0.01 -g wing stiffness/strength requirements. The 0.22-m (8.6-in) diameter mast is constructed from fiberglass longerons and battens and stainless steel braided cable diagonals. The stowage canister is thin gage aluminum.

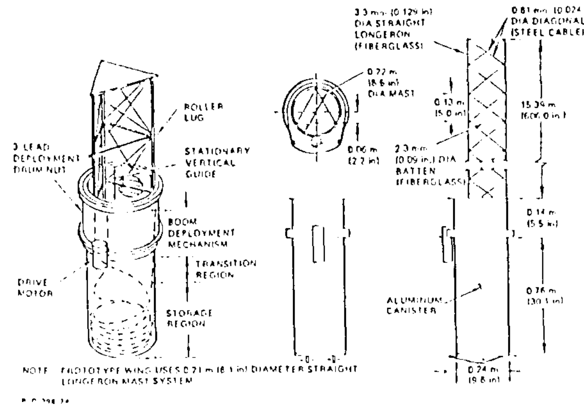

Fig. S. Wing deployment mast system.

3. RECENT PROGRAM ACTIVITIES

3.1 SAMPIE Panel

In support of the NASA/LeRC Solar Array Module Plasma Interaction Experiment (SAMPIE) a series of test articles were. fabricated consisting of 1S x 15 cm square panels each with a 12-cell, soldered, series-interconnected circuit using 2 x 4 cm, thin (-75 pm) silicon BSFR solar cells with 100 μm thick AR/UV-coated ceria-doped microsheet covers. Both germanium-coated and carbon-load kapton substrate test articles were constructed, all mounted on a thick aluminum plate. The SAMPIE program will investigate high voltage discharge characteristics on-board shuttle in 1993 (Ref. 7). Plasma chamber testing of the coupons in preparation for the flight test indicate acceptable behavior in that the power loss from the. plasma interaction with the weakly conducting blanket substrates is very small (Ref. 8).

3.2 PASP-APEX Panel

In 1993, the Photovoltaic Array Space Power - Advanced PV and Electronics Experiment (PASP-APEX) will be launched for a 3 year elliptical near polar orbit mission (350 x 1850 km, 70 degree inclination) 10 measure high voltage discharge and radiation effects on advanced power designs (Ref. 9). A small panel was fabricated consisting of germanium coated kapton with a 12-cell, soldered, Series-illtcrconnccled circuit using 2.6 x 5.1 cm thin (-65 μm) silicon BSFR solar cells with 50 μm thick AR/UV coated ceria-doped microsheet covers. The blanket section is supported on an aluminum frame.

3.3 Thin Film GaAs Solar Cell Thermal Cycle Panel

The development of the peeled-film GaAs cell by Kopin Corporation has the potential to improve the specific power and power density performance of the. Al'SA allay design by almost 40 percent, because the. cell stack combines a mass less than a thin silicon cell stack with a photovoltaic conversion efficiency slightly greater than conventional thick GaAs/Ge cells. A 2 x 4 cm cell (5 to 10 μm thick), when combined with a 50 to 100 μm cove.rglass weighs from 170 to 270 mg and has a 28°C AM0 efficiency of 191020 percent, compared 10 13.8 percent for a thin silicon cell stack weighing 290 to 390 mg. Two 1 ?.-cell solder-interconnected circuit panels (Figure 6) were. fabricated to evaluate the producibility of interconnected circuits and to evaluate long term thermal cycle performance. The thermal cycle tests, beginning in mid-1993, will be similar to those successfully performed on thin silicon cell panels (Ref. 10), and will simulate 30 year GEO (-170 to 60°C) and 10 year LEO (-100 to 100°C) conditions.

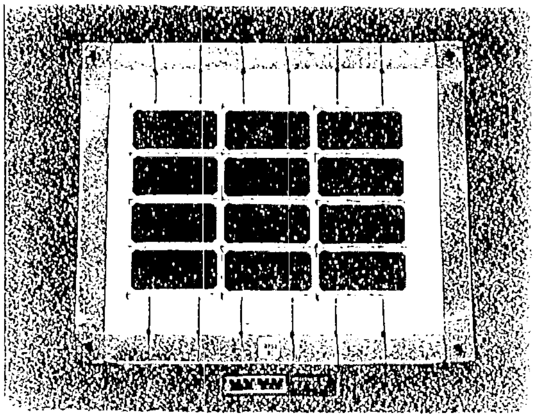

Fig. 6. Kopin CLEFT GaAs solar cell thermal cycle panel.

Several techniques were investigated to join an interconnector to the thin gold contact pacts that are supported by the DC93500 silicone adhesive layer that bonds the cover to the ultra-thin CLEFT cell. Thermosonic and ultrasonic bonding of gold ribbon or wire or aluminum wire were attempted using micro-electronic wiring production techniques normally used for large-scale integrated circuits. The results were unsuccessful because the soft DC93500 adhesive support layer did not provide sufficient rigidity to permit intermetallic joining of the ribbon/wire to the contact pad. Other attempts were very Successful when a rigid epoxy adhesive was substituted for the space-qualified silicone adhesive. However, since the epoxy adhesive is not space-qualified for solar cell stack applications, it was not used in the test panels. Instead a special inplane relief loop, silver-coated, Invar interconnector was developed and successfully joined to the gold contact pads with a tiny preform of low-temperature (143°C) indium-silver solder. A special electrode, slightly larger than the contact area, was used with low pressure (<200 mg) to minimize deformation of the contact pad or the chevron-shaped thermal relief fingers that connect the, contact pad to the cell body. (Figure 7).

The results suggest that more development work is needed at the. Cell-level and at the circuit production level before cells of this type can be considered a viable cost-effective or weight-effective option to current production "bulk" silicon or GaAs/Ge cells. However, this initial effort indicates the potential for future very high specific performance blanket designs.

3.4 Solar Cell and Circuit Reverse Bias Testing

A comprehensive coupon-level testing and analyses effort is in progress to determine weight- and cost-effective measures to ensure electrical integrity of the solar cell circuits against hot spots resulting from shadowing or cell breakage which will occur for flexible blanket arrays. This activity represents a more indepth effort than the 1991 effort which concluded thin wafer diodes would be needed for every eight thin silicon solar cells.

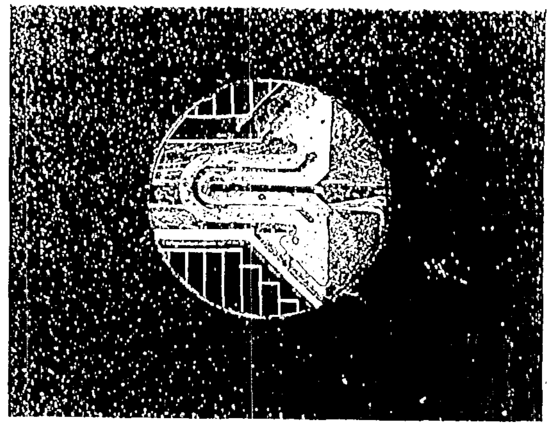

Fig. 7. Interconnection detail, Kopin CLEFT GaAs solar cell.

Work has just been completed on measuring the reverse bias characteristics and failure modes on 200 thin BSFR flight production cells from two United State.s suppliers. Testing was done as a function of temperature, short circuit current level, repetitively pulsed reverse bias conditions, long duration reverse bias conditions, and charged particle irradiation conditions. Figures 8 and 9 illustrate the wide variation in reverse breakdown voltage at ambient temperature. There were distinctive differences in the results from the two suppliers, one having a large spread in characteristics, with breakdown occurring from 10 to 65 volts at a current density level ~1x I_{sc}; and the other characterized by a narrower spread with high voltage (45 to 65 V) and low current density (-0.2 x I_{sc}). The difference in behavior is thought to be due to the methods used in producing the back surface field (boron doping versus ion-implantation). The effects of temperature level, pulsed or long duration reverse bias conditions or radiation on the reverse bias characteristics were small. Failure modes for both types of cells were either by shunting or shorting; open circuit failures did not occur. Failure modes were observed via IR thermography, with follow-up evaluation using scanning electron microscope and energy dispersive X-ray analyses on failure sites.

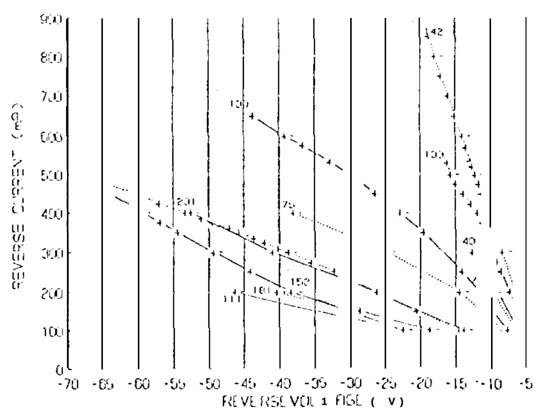

Fig. 8. Reverse bias characterization of Boron diffuse thin BSFR silicon solar cells (Cell taken to failure).

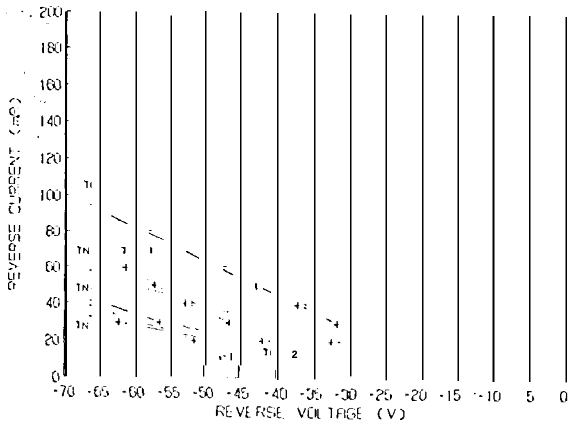

Fig. 9. Rc.verse. bias characteristics ion-implanted thin silicon BSFR solar cells.

As part of the solar cell characterization activities, large area (0.5 x 2.4 cm), relatively thick (380 µm) waft.r diodes were obtained from a domestic supplier and characterizes under forward and revel se conditions; al temperature, under long duration conditions and after charged particle ir radiation. Circuit tests at ambient conditions were also performed with bypass diodes to better understand how the effects of shadowing, crack cells, bus voltage level, and the cell rever sc bias characteristics impact the performance of the solar cell circuit. These circuit test results, in conjunction with the solar cell and diode test results, are now being analyzed 10 obtain guidelines that will define the number of series-interconnected thin silicon BSFR cells that newel to be protected with a wafer diode. initial analyses suggest that the definition of a weight- and cost-effective circuit protection design may be highly dependent on the solar cell reverse bias characteristics, bus voltage level, heat conduction properties of the blanket substrate, and the type of cell cracking or nature of circuit shadowing.

4. PROTOTYPE WING HARDWARE ACTIVITIES

Figure 10 shows the. initial version of the. deployed prototype wing on an air bearing deployment test fixture. The prototype wing is representative of the 5.8 kW (1101,) wing except in five respects: (1) it is truncated in length, consisting of an 8-panel blanket assembly (-3 rn long), with two 3-panel SPAS and two 1-panel leader panels, instead of a total of 42 panels; (2) the blanket panels incorporate 14402 x 4 cm (instead of? x 5.7 cm) live thin silicon solar cell modules soldered interconnected to obtain a Series of high voltage circuits ranging from SO to 150 V (1 20 10 360 cells in series), with the. rest of the. SPA area covered with mass-simulated aluminum blanks; (3) the live solar cell modules arc representations of flight- quality cells/covers (covers arc. uncoated ceria-doped glass rather than being AR/UV-coated and the cells are electrically active, although they c1o not necessarily possess high electrical performance characteristics); (4) the.le. arc no bypass diodes included in the solar cell circuits; and (5) construction is being done, to standards consistent with the prototype nature of the hardware rather than to flight-quality standards.

As discussed in Ref. '2 the 8-panel version of the wing was subjected to a set ics of system-level tests where.by the stowed wing was exposed to acoustic and vibration conditions simulating the envelope of Shuttle and Atlas launch environments. Stowed wing first mode natural frequency was about 34117,. In local areas of the blanket housing structure the vibration response g-loads reached 25 g's under a 10-g sine dwell base shake test. 'J'here. was negligible. change in the. 5200 Pa (0.75 psi) stowed blanket preload pressure. Deployment testing of the wing after exposure to these. environments indicated that the preload/release mechanism operated smoothly and the blanket deployed in a controlled accorclirrrl-like fashion. Inspection of the primary structure revealed no damage. After the. two acoustic tests 4 percent of the. cove.rs and 0.2 percent of the live. cells were cracked. After the. eight vibration tests, an additional 0.7 percent of the covers and 1 percent of the live cells were. cracked, All cell cracks were considered minor. Electrical continuit y was maintained in all solar cell strings.

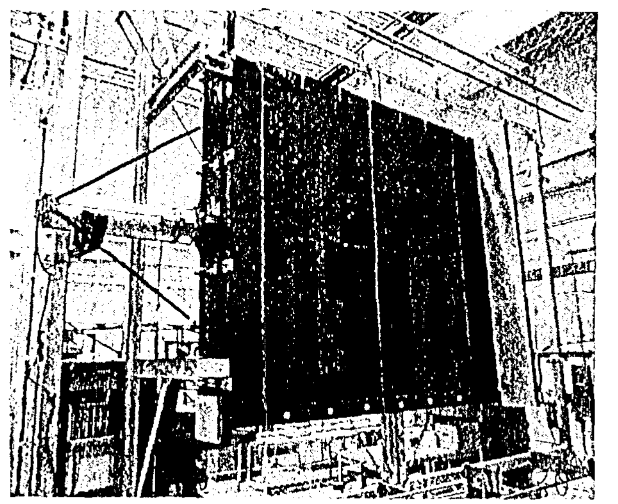

Fig. 10. Deployed prototype wing.

The 8-panel wing was then re-built into a 12-panel assembly, thereby extending the wing length by 50 percent to -4.4 m long. The added blanket panels include 480 thin silicon cells, bringing the. total number of silicon cells on the blanket assembly to 2200 cells. Also about 300 thin (1 15 µm) 2 x 4 cm GaAs/Ge cells were. added. The coverglass for the new cells was edge etched, whereas the cove.rg,lass for the initial 1440 silicon cells was unetched. The wing in this configuration was subjected to a set ies of stowage. and deployment tests, resulting in about 3 percent additional cracked covers, 0.5 percent additional cracked silicon cells and 7 percent cracked GaAs/Ge cells. Electrical continuity was maintained in all circuits.

The wing was then modified under TRW discretionary funding 10 incorporate a full size germanium-coated, laminated Kapton/ composite substrate in place of the inboard 3-panel SPA, along with a blanket inboard leader panel. The 3-panel SPA included about 1902 x 4 cm, 140 µm thin GaAs/Ge cells and 1804 x 4 cm, 90 µm thin GaAs/Ge cells, all with 150pm cz.lia-dope.d microsheet covers. The wing was subjected to simulated 10 g launch vibration testing rrnd subsequent deployments. Only onc additional silicon cell was cracked and about 0.7 percent of the GaAs/Ge cells cracked. All cell cracks were minor, with no loss in electrical continuity.

In conjunction with this latest version of the wing, a thermal cycle test panel was fabricated under TRW proprietary funding, consisting of the. laminated substrate with 722 x 4 cm GaAs/Ge cells and 40 4 x 4 cm GaAs/Ge cells and two printed circuit harness segments representative of the. blanket assembly harness. Thermal cycle. testing representative of a 1 .EO mission was initiated (-1 15 to + 100°C). After about 25 percent of the planned 40,000 cycle.s, the. power output has changed less than 1 percent. Also, about 300 GaAs/Ge cells were. tested for reverse bias characteristics. The results indicated that shunt diodes would not be required when incorporated into a laminated blanket design.

5. PERFORMANCE ESTIMATES

Currently the performance estimates remain unchanged from the 1991 Ref. 2 data for BOL and EOL specific power using thin silicon cells, thin GaAs/Ge cells or advanced thin film cells. For thin silicon cells with a waft.1 diode every 8 cells, the 1101, specific power and power density arc 138 W/kg and 140 W/m^2, respectively, for a 5.8 kW BOL wing. EOL values (at 3.9 kW) arc 92 W/kg and 94 W/m^2, respectively, for a 10 year GEO mission. The use of 18 percent efficient, thin (-1 15 pm) GaAs/Ge cells provide about the same specific power trends as the less costly thin silicon cells over the range of 51020 kW, even though the wing length would be reduced about 30 percent for comparable power levels. This is because the increased efficiency of the GaAs/Ge cell is offset by its density which is over twice that of silicon. The usc of advanced thin film cells, once their production maturity has been demonstrated, may improve specific power performance by S() to 100 percent such that 200 W/kg (EOL) might be achievable within the next 10 years.

In progress now are circuit analyses, based on the. reported reverse bias testing, to ensure that electrical integrity of silicon solar cell blankets are maintained as the result of hot spots generated from cracked or shadowed cells. While the cun ent design and performance estimates include an allocation for a wafer diode every 8 solar cells, the recent cell data indicate that the design approach may really depend on several factors including: the nature of the cell reverse bias characteristics, the circuit voltage level, the nature of shadowing or degree of cracked cells assumed. '1'bus, it is anticipated that the final APSA design and performance estimates will bc. Ic.vised to reflect updated protection guidelines.

6. APSA APPLICATIONS

The transition of Al'SA from a testbed program to a flight hardware program has finally been achieved. As alluded to in the Introduction, a derivative of the APSA design was selected for the NASA/GSFC EOS-AM solar array for the LEO polar mission. This one wing 5 kW (EOL) design will utilize 2.4 x 4.0 cm x 140 μm 18 percent GaAs/Ge cells mounted on a laminated blanket. Delivery of the first EOS-AM wing is scheduled for early 1996. The blanket size will be about 5 m wide by 9 m long and consist of 24 cell-covered panels and one. blank leader panel at each end. The total blanket assembly includes about 36500 cells with each 127 volt string having 190 series cells without [he. need for shunt diodes. Trade studies indicated the equivalent power level design using thin silicon cells would have resulted in a wing, 50 percent larger in area at a cost about 10 percent above the baseline design. The blanket box structure and mechanism and mast system for EOS-AM will bc a direct scale-up of the APSA design.

Under near normal son insolation the. wing will have. an estimated specific power performance of about SO W/kg when considering the impact of mission-specific stiffness and mechanical/electrical interfaces, and the fact that the blanket housing assembly mast system and harnesses are being sired to include a power growth potential of 20 percent. Also, the wing is being designed to incorporate about 60 kg of additional components not considered under the gene.ric APSA design. Nevertheless, the performance is relatively high because of the pathfinder work done under the APSA program.

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